Sub-400 nm film thickness determination from transmission spectra in organic distributed feedback lasers fabrication

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Highlights

- Film thickness in the range 400-40 nm is calculated from spectrophotometric trace.
- Simulation and experimental data are compared in the transparent spectral window.
- Accuracy of 5 nm is achieved even for films with low refractive index (1.5-1.7).
- Refractive index errors hinder the method applicability as thickness decreases.

Sub-400 nm film thickness determination from transmission spectra in organic distributed feedback lasers fabrication

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Abstract

The design and fabrication of thin-film based organic optoelectronic devices require knowledge of the film optical properties. A low-cost and non-destructive method often used for optical characterization of films is the well-established spectrophotometric envelope method. However, this method is typically limited to thickness above 400 nm, a value often higher than that of the films involved in these devices. This paper studies a procedure to obtain the thickness of sub-400 nm active films from their spectrophotometric trace when the refractive index is previously known. The proposed procedure is based on comparing the experimental transmission spectrum in the transparent spectral window with that obtained by simulation. The capabilities of the proposed method are demonstrated here by its application in the fabrication of organic distributed-feedback lasers where a fine control of film thickness is important to obtain an optimized and reproducible response. Results were verified with other techniques, such as ellipsometry and profilometry. Thus,

with the proposed method, film thickness can be easily determined down to 40 nm maintaining an accuracy of about 5 nm even for films with low refractive index (1.5-1.7). Different methods to determine refractive index of these films are also discussed.

Keywords

Distributed feedback lasers, Thin film thickness, Optical characterization, Transmission spectra

1. Introduction

In the last years there has been many efforts in the development of thin-film devices for organic optoelectronic applications. For their design and fabrication, it is crucial to know the film optical properties. Particularly, a fine control of film thickness is generally important to obtain an optimized and reproducible device response [1,2]. That is the case for thin film organic lasers, which have attracted great attention in the last two decades due to easy processability and the possibility of tuning the emission wavelength [3]. In particular, distributed feedback (DFB) lasers which contain a waveguide active film consisting of a dye dispersed in a polymer matrix and a surface-relief grating as a laser resonator have found a variety of applications in spectroscopy, optical communications and sensing [4,5]. In the design and fabrication of these lasers, optical constants of films coated for preparing the device must be known. Mainly, fine thickness control of the active film is important to optimize the laser response [6]. The thickness of the active layer is usually between 150 and 1500 nm and that of the photoresist film for making the resonator is even lower, between 50 and 150 nm. Refractive indexes of these materials are typically in the range 1.5 -1.7.

Various non-destructive methods are described in literature for measuring the optical constants of films. Among them, ellipsometry and spectrophotometry are widely used. One of the advantages of ellipsometry is that it is sensitive even for films of a few nanometers [7,8]. Spectrophotometry, even though has lower accuracy and is limited to thicker films, is cost-effective, and the analysis is simpler and requires less time [9]. In this paper we propose a simple method for determining film-thickness in the fabrication of DFB lasers. The proposed procedure is derived from the spectrophotometric envelope method proposed in 1976 by Manifacier et al. [10] and further developed by Swanepoel [11–13]. This well-established method, often called Swanepoel method, is based on the analysis of the interference pattern which appears in their visible and near infrared transmission spectrum, and is applicable to transparent and weakly absorbing films.

The first step in the Swanepoel method is to calculate the refractive index, *n*, at wavelengths corresponding to the interference extremes by constructing envelopes around maxima and minima that are considered as continuous functions. These refractive index values are calculated through the equation

$$n = \left[N + (N^2 - s^2)^{1/2} \right]^{1/2} \tag{1}$$

with

$$N = 2s \frac{T_M - T_m}{T_M T_m} + \frac{s^2 + 1}{2} \tag{2}$$

where T_M and T_m represent the transmission determined from envelopes at the wavelengths corresponding to the extremes of the interference fringes, and *s* is the refractive index of the substrate at those wavelengths. Then, film thickness, *d*, can be determined by the equation

$$d = \frac{\lambda_1 \lambda_2}{2(\lambda_1 n_2 - \lambda_2 n_1)} \tag{3}$$

where n_1 and n_2 are the refractive indexes at two adjacent maxima or minima at λ_1 and λ_2, respectively. In this way, the precision for films of about 1 μm, after calculating the order of interference of each fringe, can be better than 1% [11]. However, since calculations are based on the wavelength spacing of the interference extremes, the method is only applicable when at least a few interference maxima and minima of interference are available. In practice, accuracy decreases with decreasing film thickness [14] and nowadays it is stated that the envelope method is the main tool for accurate optical characterization of a film with thickness typically in the range 500-5000 nm [15]. Other authors have pointed out that its application is limited to layers of thickness larger than about 400 nm [16]. Thus, the use of the envelope method for optical characterization of active films in DFB lasers presents an important limitation because their thickness is often near or below 400 nm. Furthermore, for DFB lasers in which the relief grating is recorded in a photoresist film, the thickness of the latter is near or below 100 nm. We also note that the precise location of maxima and minima positions depends on fringe contrast, which is highly dependent on refractive index. For example, fringe contrast increases in a factor higher than 10 when the film refractive index increases from 1.5 to 2. Thus, another problem in the application of the envelope method arises from the relatively low index value of the active and photoresist films (1.5-1.7).

Here we present a spectrophotometric procedure to determine the thickness of sub-400 nm films, applicable when the refractive index is previously known. This procedure is based on the comparison in the transparent spectral window between the experimental transmission spectrum at normal incidence and that obtained by simulation. Since the comparison takes place between two continuous curves, the accuracy is high even though the useful spectral window is small. Concerning the refractive index measurement, we show that for the homogeneous spin-coated films used, it can be obtained by the standard envelope method from a thicker film of the same

material. Variations of index with dye concentration were also investigated. Remarkably, values of the active and unexposed photoresist film index and thickness obtained through the proposed method are regularly used in our laboratory for the design and construction of DFB lasers, as well as for the calculation of the predicted DFB laser emission wavelength.

2. Method and materials

We consider a thin film coated on a thick finite transparent substrate of refractive indexes *n* and *s*, respectively. The proposed method for film thickness, *d*, determination based on comparing the interference pattern which appears in the experimental transmission spectrum at normal incidence with that obtained by simulation requires to calculate the transmittance of that system. This operation is quite simple and precise when it is performed in the transparent spectral region. In this region, transmittance $T(\lambda, s, n, d)$ at normal incidence can be obtained through the following simplified model [11]:

$$T = A/(B - C\cos\varphi + D) \tag{4}$$

where $A = 16n^2 s$, $B = (n+1)^3(n+s^2)$, $C = 2(n^2-1)^3(n^2-s^2)$, $D = (n-1)^3(n-s^2)$ and $\varphi = 4\pi nd/\lambda$.

In this case, the envelopes around the extremes of the interference fringes T_M and T_m can be written in a simple algebraic form:

$$T_{\mathrm{M}} = A/(B - C + D) = 2s/(s^2+1) \tag{5}$$

$$T_{\mathrm{m}} = A/(B + C + D) = 4n^2 s/(n^4 + n^2(s^2+1) + s^2) \tag{6}$$

We also note that expression (5) coincides with that corresponding to the interference-free transmission spectrum of a thick transparent uncoated substrate [11]

$$T_{\mathrm{s}} = 2s/(s^2+1) \tag{7}$$

Thus, in the transparent spectral window transmission maxima are located on the substrate spectrum, and the window limits can be estimated by comparing the experimental spectrum of a film thick enough to have several complete fringes with that of the substrate. Finally, attention should be paid to film inhomogeneities, such as surface roughness, because they produce a decrease in the contrast of the interference fringes [12].

The comparison between the experimental spectrum data, T_{exp} and those generated from Eq. 4, T_{calc} for calculating d was performed by means of a simple Mathematica (Wolfram Research, Inc.) program in an iterative process until both spectra coincide. In the program, the experimental data, the well-known dispersion relation of the fused silica (FS) used as substrate, $s(\lambda)$, and that of the film obtained from a thick film as described in detail in section 3.1, $n(\lambda)$, are used as input and d is the output. Function given by Eq. 4 is tabulated for different values of film thickness d and compared in the transparent spectral window with experimental data. The difference between the simulated and experimental data is evaluated in the transparent window by using the sum of absolute deviations, R

$$R = \sum_i \left| T_{exp}(\lambda_i) - T_{calc}(\lambda_i) \right| \tag{8}$$

In this way, it is easy to discriminate the global minimum of R avoiding local minima to find out the real value of d.

The polymer matrix of the active film is usually polystyrene (PS) or poly(methyl methacrylate) (PMMA). Here we present measurements on PS films doped with two different laser dyes, emitting in the orange and the blue of the visible spectrum and working at low (1 wt%) and high (30 wt%) concentration, respectively. DFB lasers based on those dyes, the perylenediimide derivative *N*,*N*´-di(2,6-diisopropylphenyl)perilene-3,4:9,10-tetracarboxylic diimide, known as perylene orange (PDI-O) and the hole-transporting *N,N*´-bis(3-methylphenyl)-*N,N*´-diphenylbenzidine (TPD) have been

published [17,18]. Homogeneous films were spin-coated from toluene solutions containing the polymer and the dye on 25 mm × 25 mm and 1 mm thickness transparent FS substrates. Film thickness was varied by adjusting the percentage of PS in the solution.

The water-soluble dichromated gelatin (DCG) was used as a photoresist to fabricate DFB laser resonators [19]. After a holographic exposure, a surface-relief grating is generated by a dry development process in oxygen plasma [20]. The main advantage of using DCG respect to a standard photoresist is the immiscibility of the PS matrix (soluble in organic solvents) and the DCG film (soluble in water). So, during laser fabrication the coating of the DCG layer in solution does not affect the active film [17]. DCG films were prepared with gelatin Rousselot 13311 at 40 °C and sensitized with ammonium dichromate (35 wt%). The thickness of the resulting film, which is important because it determines the grating depth, was varied by adjusting the percentage of gelatin in the aqueous solution.

In all cases, measurements were taken against air at the center of the sample in a Jasco V-650 spectrophotometer. Besides, the experimental spectrum of the FS uncoated substrate was compared to that obtained by the theoretical expression (Eq. 7) to correct any instrumental systematic error of the spectrophotometer.

3. Results and discussion

3.1. Refractive index measurements

In order to simulate the spectrum of an active film coated on a FS substrate, the dispersion relation of the film material $n(\lambda)$ needs to be known. Although the dispersion relation of the polymer matrix (PS, PMMA, etc.) of the film is usually known, it can be appreciably modified by the

laser dye, especially when it is at a high concentration. In these cases, a convenient method for measuring the index of homogeneous and uniform spin-coated active films consists of preparing another film of the same material but thick enough to make possible the application of the envelope method, i.e., to make visible at least two complete fringes in the transparent spectral window. These films are typically between 1.0 and 1.5 μm. The spectrum of this thick film is also useful to estimate the limits of the transparent window by comparing its spectrum with that of the substrate. We assume that a material is transparent when the difference between the absorbance of the sample and that of the substrate in the interference minima is lower than 1%. According to Eq. 1, valid for weakly absorbing films, and considering the typical values of films used in the fabrication of DFB lasers (n=1.59, s=1.46), this assumption leads to an error in the refractive index smaller than 0.002 at a wavelength of 600 nm. In the last term, the lack of coincidence between the experimental spectrum and the simulation obtained through Eq. 4 allows a more precise determination of the transparent windows limits.

Figure 1a shows the experimental absorption spectrum of sample S1, a PS film doped with 1 wt% of PDI-O coated on a FS substrate. As usual in the organic electronics scientific community, results are expressed using absorbance instead of transmittance. In this case, we find that the experimental spectrum for wavelengths above 600 nm is close to that obtained by simulation for an undoped PS film of d = 1286 nm. The spectrum of the FS uncoated substrate derived from Eq. 7 has also been included. Note that the transparent spectral window begins at a wavelength ~600 nm, at edge of the dye absorption. When the PS interference pattern is extended to the spectral region where absorption is not negligible, the true absorption spectrum of the active material can be obtained by subtraction. This feature is useful when the dye concentration is low and the

interference pattern can modify appreciably the wavelength and relative intensity of absorption peaks.

INSERT FIGURE 1a AND 1b

Figure 1b shows results from a study of sample S2, a PS film doped with 30 wt% of TPD coated on a FS substrate. In this case, the transparent window begins at a wavelength ~550 nm. The simulation of the spectrum in the transparent window of a 30 wt% TPD-doped PS film of d = 1096 nm is also included. This d value coincides with that obtained by the envelope method. After different trials, we found acceptable for these materials to model the dispersion relation in the transparent window with the two–term form of Cauchy´s equation

$$n(\lambda) = A_1 + (A_2 / \lambda^2) \tag{9}$$

where coefficients A_1 and A_2 were determined by fitting the equation to calculated refractive indices from the envelope method at wavelengths of interference extremes. In case of 30 wt% TPD-doped PS films, at variance with the PDI-O case, $n(\lambda)$ is appreciably different from that of the undoped PS matrix (see inset in Fig. 1b).

Film dispersion relations obtained by this method will be useful after verifying that, in these cases, $n(\lambda)$ is independent of d. This proposition was studied through the Abelès Brewster-angle method [21,22] which is a relatively simple method to determine n in the transparent spectral window. The method is based on comparing p-polarized light intensities reflected from the sample (film/substrate) and the uncoated substrate to determine the incident angle in which both intensities are equal (film Brewster angle). The sensitivity of the Brewster angle determination depends on the angle between both reflectivity curves at the point where the curves intersect.

Thus, care must be taken because, for some film thicknesses, this intersection angle is very small and the error, which regularly is ~0.002, increases considerably [23].

Visible He-Ne gas and near-IR diode lasers emitting light at 632.8 and 828 nm, respectively were used to confirm the proposition with an error in *n* of about ±0.005. Table 1 presents results of a preliminary study on PS samples. In the case of thick films, refractive indexes were also calculated from the dispersion relation obtained after applying the Swanepoel envelope method. For comparison purposes, the refractive index of PS obtained through the deviation-angle method by Sultanova et al. [24] using an injection molded PS plate has been included.

When using laser beams for making measurements, one might consider the temperature effects. In our case, these are found to be negligible given ~~than~~ that the sample irradiation is relatively low (~ 1 mW/mm^2), films are transparent to those wavelengths and the temperature coefficient of the PS refractive index is $-1.31 \cdot 10^{-4}$ K^{-1} [25]. Concerning the influence of changes in the laboratory room ambient temperature (23 ± 3 ºC) the variation in the refractive index (±0.0005) is about five times smaller than the error of the Abelès method.

Measurements carried out with active films considered in this work are given in Table 2. The comparison between results for sample S1 and those of Table 1 shows that the dye PDI-O at a concentration of 1% does not produce an appreciable change in the refractive index of the PS matrix. On the other hand, when the dye is at a high concentration, TPD at 30%, changes are considerable. In this case, we prepared a sample S3 with an active film of thickness under 200 nm to confirm that the refractive index is also independent of film thickness (see Table 2). Refractive indexes of unexposed DCG films have also been included in Table 2. They were obtained by analyzing the interference pattern corresponding to a thick film (sample S4) in the transparent

spectral window and compared with that directly obtained by the Abelès method from a thin film (sample S5). Film thicknesses under 200 nm given in Tables 1 and 2 were determined by the procedure proposed in this paper. Finally, we note that even though $n(\lambda)$ seems to be independent of *d* for the homogeneous spin-coated films considered here, it is typically not the case for films deposited by evaporation or sputtering methods, where grain growth is usually dependent on film thickness. In fact, a study presented in the last section of the work shows that the limit of the proposed procedure is due to the increase of the refractive index for very thin films.

INSERT TABLE 1

INSERT TABLE 2

While making experiments with different dye concentrations, we found out that the film refractive index obeys laws applied regularly to particle suspensions. The simplest is the Arago-Biot additive equation

$$n = \Phi_1 n_1 + \Phi_2 n_2 \tag{10}$$

where subscripts 1 and 2 would be referred to the matrix and the dye, respectively. Φ_i (i = 1,2) represents the volume fraction of each component [26]. Figure 2 shows refractive index at 632.8 nm of several PS films doped with different concentrations of PDI-O and TPD obtained by the Abelès method as a function of the volume fraction. This wavelength is inside the transparent spectral window in all cases shown in Fig. 2.

Concerning TPD doped PS films, weight concentration numerically equals volume fraction since mass densities of TPD and PS are approximately the same (1.1 g/cm^3). On the other hand, density of PDI-O is about 1.4 g/cm^3, so weight concentration is appreciably different of volume fraction. It can be seen that for the practical range of concentrations explored, linearity confirms the suitability of

the equation in both cases. Proportionality between refractive index and dye concentration was previously observed by Oki et al. in active films of PMMA with different dopants [27]. The index of the polymer PS and that corresponding to a TPD neat film shown in Fig. 2 were taken from Sultanova et al. [24] and Holzer et al. [28], respectively.

INSERT FIGURE 2

3.2. Thickness determination of sub-400 nm films

Once $n(\lambda)$ in the transparent spectral window is known, the interference pattern can be simulated and d for the film of interest determined. Since the spectral comparison takes place between two continuous curves, the accuracy of the proposed method is high and very thin films can be measured. First we present examples of sub-400 nm active films corresponding to two new samples with thickness between 200 and 300 nm. Figure 3 shows results in the transparent spectral window for samples S6 and S7 with PS films doped with 1 wt% of PDI-O (Fig. 3a) and 30 wt% of TPD (Fig. 3b). After comparing simulations with the experimental traces, thicknesses of 230 nm and 288 nm were obtained for samples S6 and S7, respectively. Simulations for other thickness values have been included in both figures to show that accuracy is approximately 5 nm. This accuracy is comparable to that given by Swanepoel (±3 nm) analyzing data obtained from maxima and minima corresponding to 5 interference fringes in a film of $n \sim 3$ and $d \sim 1$ μm [11]. Note that a near-infrared spectrophotometer covering a wider wavelength range would be used for dyes emitting in the red of the visible spectrum.

INSERT FIGURE 3a AND 3b

The capabilities of the proposed method have been further explored by performing measurements on other types of films. Particularly on the DCG photoresist films used to prepare the laser resonators. Film thicknesses below 150 nm of unexposed DCG are regularly measured in our laboratory through the proposed method. As an illustrative example, we present here results for two samples. Figure 4 shows results in the transparent spectral window corresponding to samples S8 and S9 with unexposed DCG films, which thicknesses were determined to be 120 and 37 nm, respectively. In these cases, the transparent window begins at a wavelength ~630 nm, and spectra for wavelengths higher than 850 nm have been omitted because they are very noisy. Note that when films of low *n* are very thin and there is no any minimum in the transparent window, it is essential to correct any systematic error of the spectrophotometer by means of a comparison between an additional uncoated substrate spectrum and the theoretical function corresponding to the substrate (Eq. 7). These absorbance corrections were around -0.0005. Simulations corresponding to films of other thicknesses included in Fig.4 show that the accuracy of about 5 nm is maintained.

INSERT FIGURE 4a AND 4b

Results corresponding to samples S6-9 were compared with those obtained with a stylus profiler Ambios XP-1 (Table 3). In contrast to the proposed method, which averages a measuring area of the slit image in the spectrophotometer of about 1 mm × 7 mm, thickness determined by profilometry provides only a punctual measurement. So, in these cases, results were obtained as the average of three measurements at approximated locations (-3, 0), (0, 0) and (0, 3) mm from the center of the sample. It can be seen that both methods provide similar results. Thus, the proposed procedure appears as a good alternative to profilometry, one of the most standard methods used for this purpose, which has the drawback of being destructive.

INSERT TABLE 3

The limit of the proposed method has been studied by performing measurements on very thin PS films. We chose this material because it is highly stable, at variance with unexposed DCG films, which must be manipulated under security light and are sensitive to temperature and humidity changes. In this study, highly accurate measurements have been carried out by variable angle spectroscopic ellipsometry (VASE) on five PS films, with thickness in the range 20-160 nm, spin-coated on FS substrates. We used the M-2000U system, which averages data from a measuring area of 4 x 5 mm. Results are compared to those obtained with the procedure proposed in this paper (see Table 4). All measurements were performed in the central part of the samples.

INSERT TABLE 4

Results show that errors in *n* determination hinder the application of the proposed method as the thickness decreases. Figure 5 shows variations of *n* obtained by VASE. The refractive index dispersion curve for PS obtained through the deviation-angle method by Sultanova et al. [24], which matches *n* values obtained from PS thick films (>1 μm) obtained through Swanepoel envelope method with an error smaller than 0.005, has been included. It can be seen, that for very thin films *n* increases when *d* decreases. This tendency was previously observed with samples of polyarylate between 15 and 140 nm [29]. Column 3 in Table 4 shows that when the respective dispersion curve obtained by VASE is used as input to simulate the spectrum, film thickness error is reduced to ~1 nm. So, we conclude that the proposed method can be applied for measuring the thickness of active and photoresists films with an error of ~5 nm thicknesses above ~40 nm (see results for sample S9 in Table 3). However, when film thickness is lower than 80 nm, it would not be advisable to determine the refractive index from a thick film by the

Swanepoel method. In these cases, the Abelès method can be a good option for obtaining the refractive index in the transparent spectral window.

INSERT FIGURE 5

4. Conclusions

We have shown that the thickness of films for the fabrication of organic DFB lasers in the approximated range 400-40 nm can be determined by comparing the experimental transmission spectrum to that obtained by simulation in the transparent spectral region. Results are comparable to those obtained from profilometry. Remarkably, the reported procedure has an accuracy of about 5 nm even though experiments were carried out with low refractive index films (1.5-1.7). This accuracy is comparable to that obtained with the standard envelope method for high refractive index films (~3) of around 1 μm. We have also shown that the refractive index can be obtained by the spectrophotometric envelope method from a thicker film of the same material. However, care must be taken when applying the method to films thinner than 80 nm because the refractive index might change. The strategy of working in the transparent window, where the absorption can be neglected, allows to measure the refractive index through the Abelès method and to model the dispersion relation by the simple two-term form of Cauchy's equation. We also find that, when the concentration of the dye in the active film is changed, the Arago-Biot additive law is satisfied. Finally, we note that this procedure could be applied not only to the active and the photoresist films of organic distributed feedback lasers, but to other kind of films, organic or inorganic, whenever they have a transparent spectral window of at least a few hundred nanometers.

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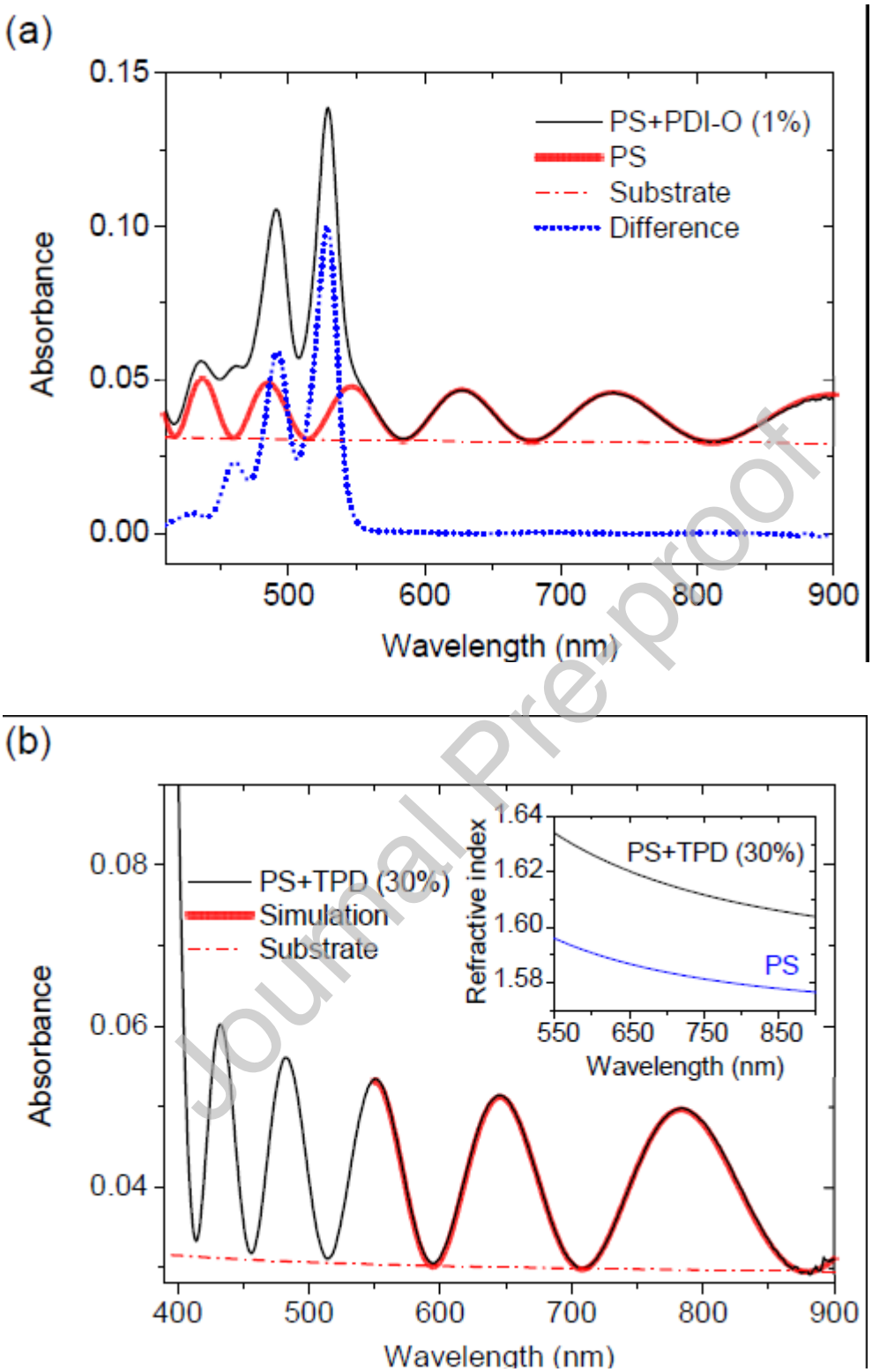


Fig. 1. Experimental absorption spectra against air (black solid line) corresponding to PS films doped with (a) 1 wt% of PDI-O (sample S1) and (b) 30 wt% of TPD (sample S2), respectively. The substrate

function derived from Eq. 2 is also included in both figures (red dash-dotted lines). In (a), a pure spectrum of the active material (blue dotted line) is obtained from the simulated spectrum of an undoped PS 1286 nm film (red thick solid line). In b), the simulated spectrum of a 1096 nm film is shown in the transparent spectral region (red thick solid line). Inset shows refractive index differences between the active material and the PS matrix.

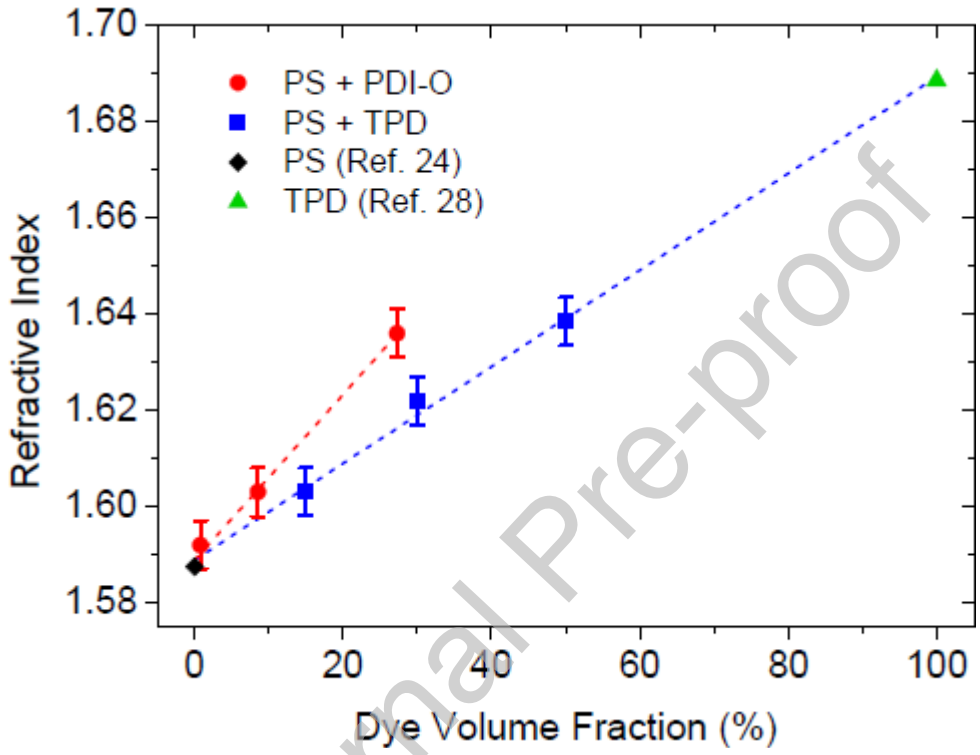
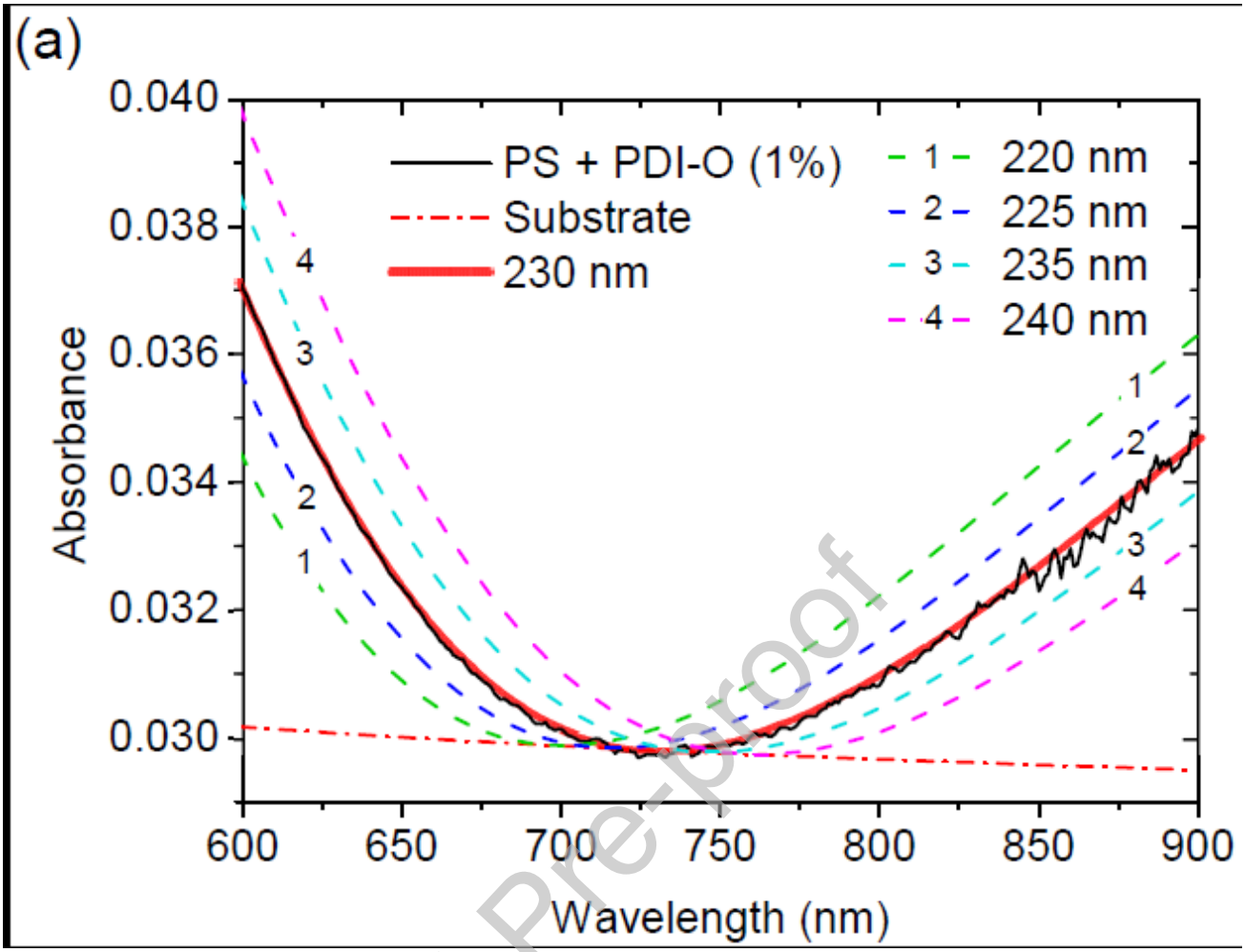


Fig. 2. Refractive index of PDI-O and TPD doped PS films measured through Abèles method at 632.8 nm as a function of dye volume fraction. In all cases shown, this wavelength is in the transparent spectral window.



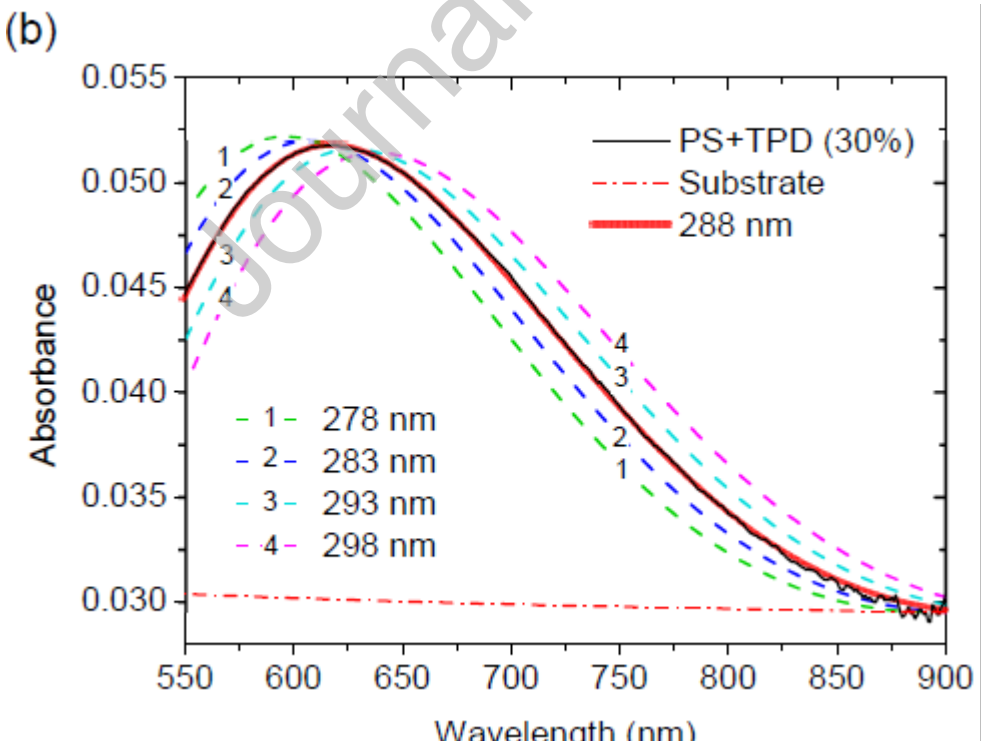


Fig. 3. Experimental absorption spectra against air (black solid lines) and simulated interference patterns for different thicknesses (red thick solid and dashed lines) corresponding to PS films doped with (a) 1 wt% of PDI-O (sample S6) and (b) 30 wt% of TPD (sample S7). Spectrum and simulation coincide for thicknesses of 230 nm and 288 nm in (a) and (b), respectively. The substrate function derived from Eq. 2 has also been included in both figures (red dash-dotted lines).

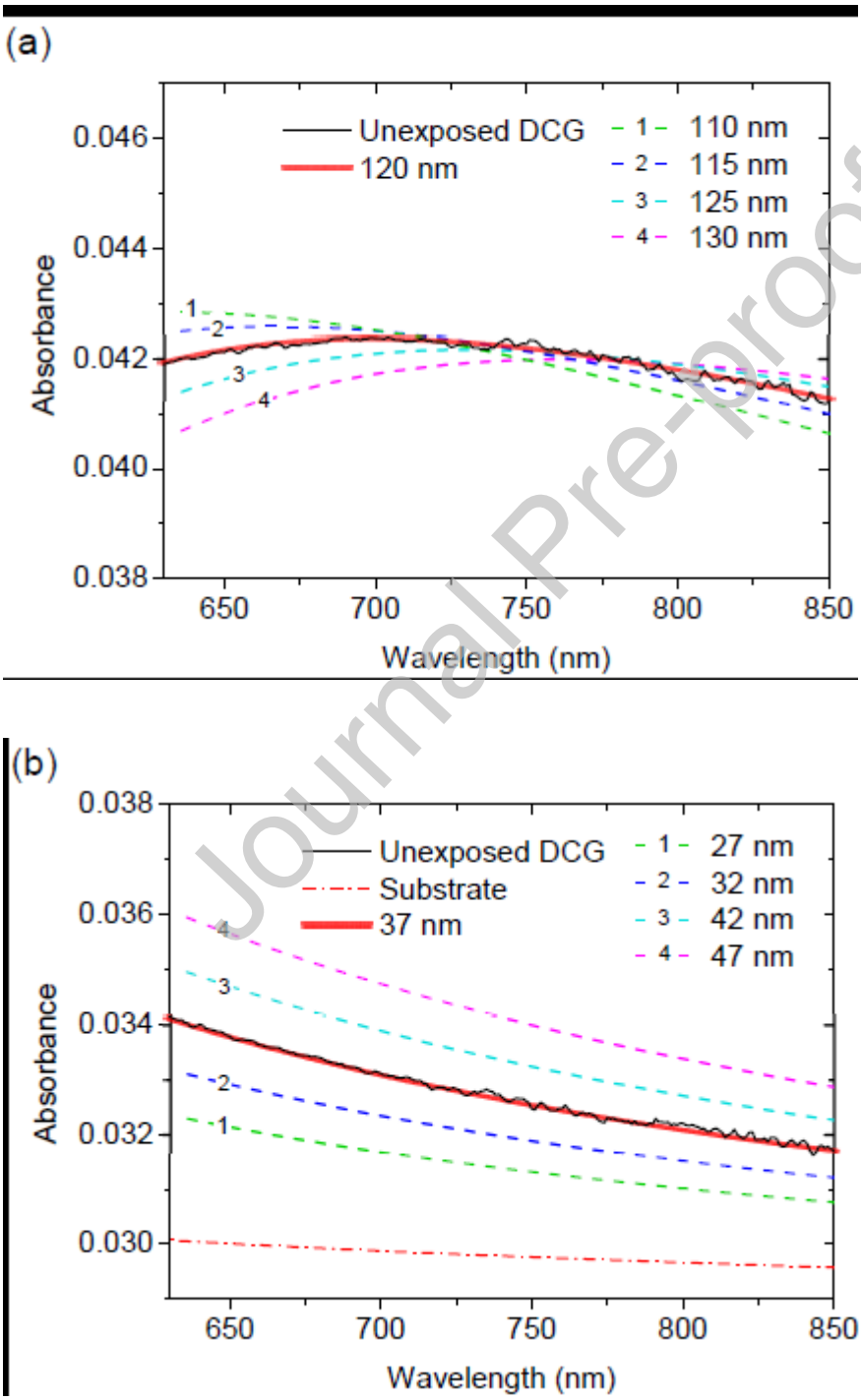


Fig. 4. Experimental absorption spectra against air (black solid lines) and simulated interference patterns for different thicknesses (red thick solid and dashed lines) corresponding to unexposed DCG films. Spectrum and simulation coincide for thicknesses of (a) 120 nm (sample S8) and (b) 37 nm (sample S9). The substrate function derived from Eq. 2 (red dash-dotted line) has also been included in (b).

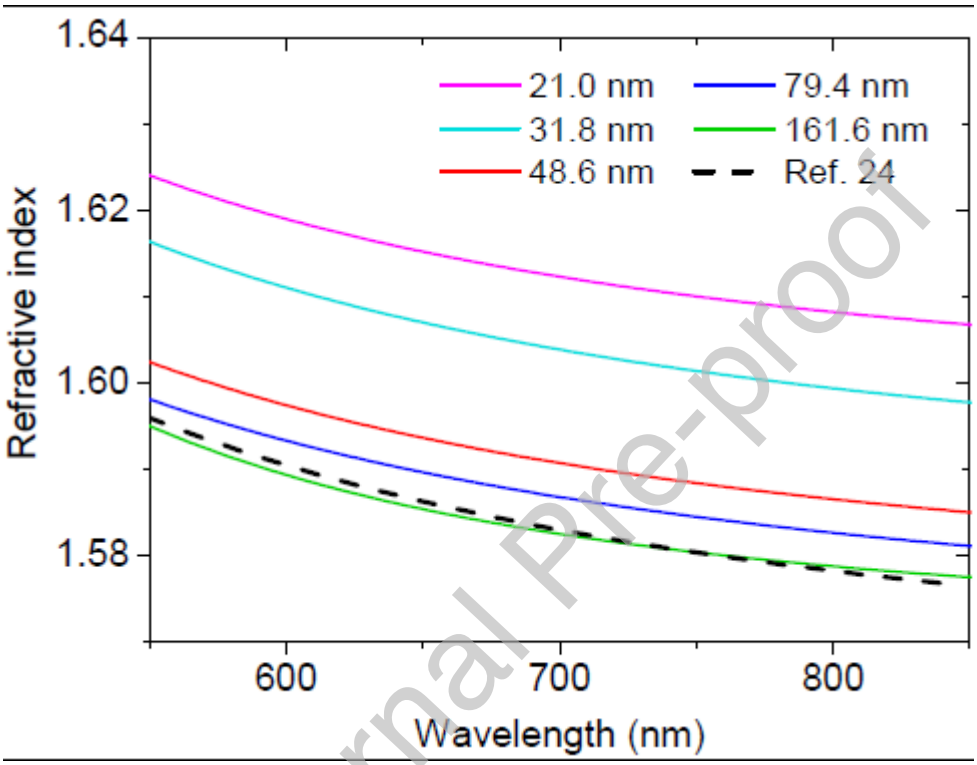


Fig. 5. Dispersion curves of PS films in the range 20-160 nm obtained through VASE. Curve from Sultanova et al. [24] for bulk PS samples is included (dashed curve).

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PS samples	Method	*n* (632.8 nm)	*n* (828 nm)	*d* (nm)
PS film - 1	Swanepoel	1.586	1.575	1530
PS film - 1	Abelès	1.591	1.582	1530
PS film - 2	Abelès	1.589	1.582	198*
PS injection molded plate [18]	Deviation angle	1.5875	1.5771	-

* Film thickness measured by the procedure proposed in this paper.

Table 1 PS refractive index measurements at wavelengths 632.8 and 828 nm using different methods.

Sample	Material	Method	*n* (632.8 nm)	*n* (828 nm)	*d* (nm)
S1	PS+1% PDI-O	Abelès	1.592	1.579	1286
S2	PS+30% TPD	Swanepoel	1.622	1.607	1096
S3	PS+30% TPD	Abelès	1.626	1.607	181*
S4	Unexposed DCG	Swanepoel	1.581	1.573	1370
S5	Unexposed DCG	Abelès	1.585	1.576	37*

* Film thickness measured by the procedure proposed in this paper.

Table 2 Refractive index at wavelengths 632.8 and 828 nm of active and photoresist films considered in this work.

Sample	Material	*d* (nm)	
		Proposed procedure*	Profilometry*
S6	PS+PDI (1%)	230	220
S7	PS+TPD (30%)	288	291
S8	Unexposed DCG	120	126
S9	Unexposed DCG	37	31

*Film thickness error: ±5 nm

Table 3 Comparative film thickness measurements by using the spectrophotometric proposed procedure and profilometry.

Sample	d (nm)		
	VASE*	Proposed procedure	
		n from Swanepoel§	*n* from VASE#
PS film - 3	21.0	27	21
PS film - 4	31.8	37	33
PS film - 5	48.6	52	50
PS film - 6	79.4	82	79
PS film - 7	161.6	161	161

Film thickness error: * ±0.5 nm, § ±5 nm, # ±2 nm

Table 4 Comparative film thickness measurements by using VASE and the spectrophotometric proposed procedure.